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ATMOSPHERIC TRANSMISSION MODELING: PROPOSED AEROSOL METHODOLOGY WITH APPLICATION TO THE GRAFENWÖHR ATMOSPHERIC OPTICS DATA BASE

Robert E. Roberts

December 1976

INSTITUTE FOR DEFENSE ANALYSES
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ABSTRACT

Using Mie calculations for a wide variety of measured and assumed particle size distributions, we have established a strong relationship between the total volume content of the particulate along the transmission path and the aerosol extinction coefficient. We have also used field measurements, such as those taken at Grafenwöhr, Federal Republic of Germany, to further establish the validity of this relationship. Both theory and experiment suggest that a phenomenological scaling of photopic transmission (related to normal meteorological visibility) to the infrared (IR) windows is possible which furthermore is independent of the structure or shape of the particle size distribution. A second important implication is that a simple, possibly remote measurement of a quantity related to the volume or mass of the aerosol could provide a direct measure of the IR transmission (an IR visibility meter). Such a routine meteorological measurement would clearly be of use to sensor performance modeling.

ACKNOWLEDGMENTS

The author gratefully acknowledges the many contributions of Lucien M. Biberman of IDA and the stimulating discussions with him. In addition, he thanks Ronald Pinnick of the ECOM Atmospheric Sciences Laboratory for his collaborative efforts and Barry S. Katz, White Oak Laboratory, Naval Surface Weapons Center, for providing the author with his maritime results.

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CONTENTS

I. INTRODUCTION

Making valid predictions of the effects of changing weather conditions on sensor performance remains an outstanding problem in the design and development of improved electro-optical (E/O) imaging systems. For a better understanding of the weather-performance relationship two kinds of questions must be addressed. In the first kind, one is primarily concerned with the statistical analyses that eventually lead to the procurement of one system rather than another. A pertinent example in this category is whether a forward-looking infrared (FLIR) device or an active TV will operate most effectively in a particular scenario such as a Central European winter environment. The second kind of question, which represents more of a deterministic approach to sensor performance, influences the deployment of a system. For example, if the weather conditions at a given time and place are either known or predictable with confidence, one must determine which system or option is preferable. Another apparently subtle yet important question along these lines addresses the selection of an optimal spectral band within a single atmospheric window. The key to answering any of these questions in a rational way is the availability of a valid atmospheric transmission model to provide the quantitative link between our extensive meteorological data base and actual performance.

By far the most practical and widely used of the current atmospheric models is the so-called LOWTRAN 3 computer code*

*LOWTRAN is the generic name of an evolutionary atmospheric transmission model developed at AFGL. The most recent publication describing this code is represented by Ref. 1. It should be noted that LOWTRAN 3 has been further updated into two newer codes designated LOWTRAN 3a and LOWTRAN 3b which include an improved water vapor continuum as well as several additional aerosol models.

developed by Selby and McClatchey of the Air Force Geophysics Laboratory (AFGL). Although this routine is adequate for defining the broadband atmospheric window regions and provides a reasonably accurate description of the uniformly mixed gas molecular absorption,* it does not fare so well in describing the degradation of image propagation by the major culprit, namely aerosols.

Several points are well worth noting with respect to the two major atmospheric constituents (namely water vapor and aerosols) and their influence upon sensor performance. First, they represent the two most important radiation attenuators in the atmospheric windows, and second, they tend to fluctuate both temporally and spatially with varying weather conditions. Since the attenuation due to water vapor is primarily a function of absolute humidity and temperature, it does not affect sensors to any appreciable degree in dry winter or desert-type climates. However, it can be a major factor in humid summer or tropical conditions, particularly for long working ranges such as those which might be encountered at sea. The effect due to aerosols depends not only upon the amount of aerosol as monitored by the meteorological visibility at the mesoscale level or the particle size distribution at the microlevel but also upon the composition of the particulate matter (i.e., sea spray, fog, dust, smoke). The aerosol contribution dominates in dry winter or desert operation and is significant during the summer months as well. For most problems of interest the aerosol component is more complex to model and a more significant influence than water vapor.

The purpose of this paper is to propose a simple phenomenological aerosol model and to review some recent field transmission measurements such as those conducted at Grafenwöhr, Federal Republic of Germany, by the Army Night Vision Laboratory (NVL).

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*The H_2O vapor is not strictly considered to be a uniformly mixed gas since its concentration or mixing ratio changes with absolute humidity.

Because the reduction of such field measurements by traditional Mie theory calculations imposes such extensive and stringent demands both upon the amount and quality of data and upon the computational machinery, we have sought a more promising and flexible avenue of approach to the calculation of propagation through aerosols. We do not attempt, in this paper, to provide an established aerosol theory.* Rather we attempt to provide the basis from which such a theory can evolve.

*The individual comprehensive models for limited visibility conditions in either a continental or a maritime environment will be the subject of a forthcoming set of papers.

II. AEROSOL MODELING

To be of use in the operational planning of E/O missions our weather measurements and forecasting must have the capability of predicting IR image propagation. This means that we must either make better use of our present data collection techniques with updated transmission models or determine which new meterological measurements are necessary for an improved understanding of the IR windows. Two separate and distinct mechanisms are involved in the attenuation of infrared and optical signals, i.e., the amount of radiant energy transferred by the atmosphere is determined by two principal types of constituents, namely gaseous molecules and aerosols or particulates with their respective attenuation coefficients β_{mol} and β_{aer}. At a particular wavelength λ the transmission is given by

$$T_\lambda = \exp\ (\beta_{tot}\ L) \quad , \tag{1}$$

where the total attenuation coefficient is $\beta_{tot} = \beta_{mol} + \beta_{aer}$ and L represents the path length. The magnitude of β_{mol} or β_{aer} clearly depends upon the optical properties, atmospheric concentration, and temperature of the molecular or particulate species.

In a previous paper by Roberts, Biberman, and Selby (Ref. 2), the problems of determining proper values of β_{mol} for the 8-12 μm region were covered in some detail with emphasis on the dominant water vapor attenuation. The conclusion of that paper was that in the absence of significant aerosol effects a more realistic sensor performance analysis is now possible.

The problem of predicting better values of β_{aer} remains an outstanding problem and is the subject of a current study under the sponsorship of the Director of Defense Research and Engineering (Research and Advanced Technology).

It is possible, under well-controlled circumstances, to measure the composition and size distribution of atmospheric particulates and then to use this information through a Mie scattering calculation to predict the transmission characteristics. Unfortunately, such a measurement is far from routine, and even if it were routine it might still be inadequate due to spatial inhomogeneities and temporal fluctuations along the atmospheric transmission path. It would therefore seem advisable, if not necessary, to adopt a so-called thermodynamic or phenomenological methodology that does not depend upon the direct measurement of the particle distribution.

The current LOWTRAN aerosol model, for example, uses measured optical properties (representative of average continental, rural, urban, or maritime conditions) with a prototypical distribution to predict via a Mie computation a scaling model for the extrapolation of the visual range to IR transmission. The scaling law used in LOWTRAN is not intended to hold for fog conditions. It also will not apply correctly for high humidity conditions but holds for a range of intermediate conditions within the accuracy to which the visual range is usually known. Even though this is a step in the right direction, the underlying assumption is that for a particular environment, such as a continental haze, the shape or functional form of the distribution remains unchanged. In many, if not most, cases this is not a valid representation. For example, in an evolving fog formation the water droplet distribution tends to grow in the sense that there are relatively more large particles as the visibility becomes lower. This is illustrated dramatically in Fig. 1, where we have plotted some representative particle size distributions

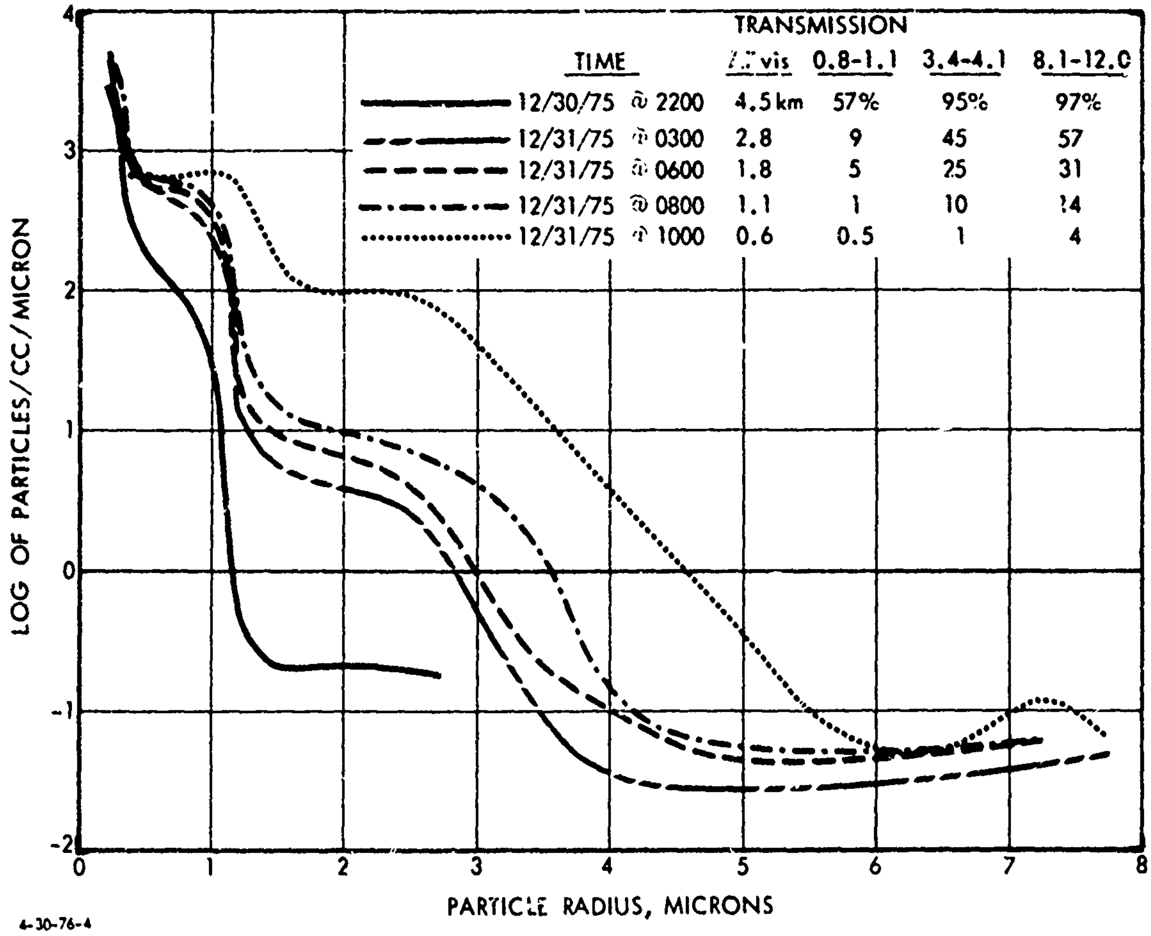

FIGURE 1. Particle Size Distributions as Measured in Grafenwöhr, FRG, during Fog Formation.

as measured in Grafenwöhr, FRG. It is, of course, impossible to accommodate such an effect with any single distribution.

In the remainder of this section we shall reexamine some of the aspects of Mie scattering theory* with the intent of motivating a simple and more general scaling model that does take into account such changes but does not depend explicitly upon either a measured or an assumed size distribution.

Although our application in this paper will be to water droplet or fog measurements, the arguments used to postulate the scaling model are generally valid for other particulates as well.

For a specified wavelength λ that is large compared to the particle radius r, the Mie extinction cross section σ_{ext} behaves in the following way for an absorptive medium:

$$\sigma_{ext} \sim r^3 \quad , \tag{2}$$

where the proportionality constant depends upon the wavelength-dependent complex index of refraction. The total aerosol extinction coefficient β_{aer} is given by the average over the particle size distribution n(r) via

$$\beta_{aer} = \int \sigma_{ext}\, dn \sim \int r^3\, dn \quad . \tag{3}$$

Hence, in this limit, which should be appropriate for IR radiation and light fogs or hazes, the aerosol attenuation at a given wavelength depends only upon the third moment of the distribution or specifically the total volume V of particulates, in a straightforward linear fashion:

*It is not our intent to provide a detailed outline or derivation of the Mie scattering equations. The interested reader is referred to any one of a number of useful texts on this subject, such as Refs. 3 or 4.

$$\beta_{aer} \sim V \text{ (long wavelength absorptive limit)} \quad . \qquad (4)$$

If we next examine the other extreme, sometimes referred to as the geometric limit, where the particles are typically large compared to the wavelength of the radiation, then large-particle scattering dominates, and we have

$$\sigma_{ext} = 2\pi r^2 \quad . \qquad (5)$$

Once again a size averaging yields the desired result, related now to the effective area A for the given distribution as in Eq. (2):

$$\beta_{aer} \sim \int r^2 \, dn \sim A \text{ (short wavelength limit)} \quad . \qquad (6)$$

This result should hold well for visible radiation transmission through fogs and rain. Assuming real-world distributions are well behaved, one might on the basis of Eqs. (4) and (6) postulate the following scaling law:

$$\beta_{aer} \text{ (long wavelength)} = C_\lambda \, \beta_{aer}^{3/2} \text{ (short wavelength)} \; , \qquad (7)$$

where the proportionality constant C_λ depends only upon the spectral bands of interest and the particle composition. Equations (2)-(4) refer to the so-called Rayleigh scattering region for absorbing particles (such as small water droplets in the 10 μm wavelength region), and Eqs. (5) and (6) refer to the geometrical scattering region. Equation (7) attempts to simplistically relate the Rayleigh and geometrical scattering regimes. Although this limit might be appropriate for the scaling of visible transmission data to the 10 μm infrared window, it is not our intent to formulate a general and practical scattering model on this basis. For example, with distributions containing a large number of particles having $r > 10$ μm the long wavelength limit is not reached, and Eq. (7) will not be valid. It would appear, however, that for most fog-like conditions the assumption for Eq. (7) is more nearly true. A validation of this assumption will be made in the following sections. Equation (7) differs from the current LOWTRAN aerosol model (Ref. 1), which essentially provides a linear scaling for all wavelengths:

$$\beta_{aer} \text{ (long wavelength)} = C_\lambda \, \beta_{aer} \text{ (short wavelength)} \ . \quad (8)$$

The application of weather data to these results is usually provided by the Koschmieder (Ref. 5) relationship

$$\beta_{aer\ vis} = \frac{3.91}{v} \ , \quad (9)$$

derived using a 2% contrast transmission requirement where v is the reported visual range. For moderately clear conditions (meteorological range of 10 km or greater) the assumptions for Eq. (8) are more nearly true. Unfortunately, these are not the kinds of conditions that are normally critical in determining the limits of sensor performance/weather capability. It is the severe limited-visibility environment that is usually responsible for incapacitating an E/O system. For these cases Eq. (8) is not generally valid.

It is not our goal in this paper to necessarily determine the validity requirements for Eq. (7) or (8). Rather, we would like to provide the motivation for adopting a more general and flexible model that incorporates both extremes *and* is not restricted to a single assumed particle distribution. Although Eq. (7) is interesting in that it is insensitive to the details of the particle distribution for the cases where it could apply (i.e., 10.6 μm radiation and medium fog conditions) it is probably too restrictive for general applications. However, the arguments leading to it are relevant to that goal. In particular, since there is such a small change in the functional dependence of β_{aer} upon r (i.e., from V to $V^{2/3}$ for the extremes), it is probably not presumptuous to assume that

$$\beta_{aer} = F(V) \tag{10}$$

for any selected wavelength independent of possible realistic shape changes, etc., in the particle distribution. The critical conclusion and assumption to be tested is that *for a particular aerosol and spectral region the attenuation or extinction is most critically dependent upon the volume of particulate in the atmospheric path and not so much upon the detailed description of the distribution function.*

If this statement is a valid one (as we hope to demonstrate below), the ramifications to the modeling community are manifold.

First of all, for most weather conditions other than extremely dense fogs, Eq. (10) is most appropriate for IR radiation. This results from the fact that the typical particle sizes in hazes and fogs are usually smaller than the long wavelengths of IR radiation. For this particularly simple case the aerosol extinction is directly proportional to the volume of particulate. This will be validated in the following discussion. Therefore, a simple measurement of a quantity related to the volume of particulate along the transmission path (i.e., grams per cubic meter) could provide a direct measure of the IR transmission characteristics. Thus one could make a routine, possibly remote measurement of the IR "visual range" since it is proportional to the liquid particulate content. This kind of meteorological measurement that does not require a tedious point-to-point IR transmission measurement could in turn be used directly in the weather-sensor performance analysis. One possible measure would be the integrated backscatter from a light detection and ranging (LIDAR) system as discussed in the next section.

Secondly, in lieu of such a measurement, Eq. (10) can be exploited in order to provide an improved scaling of the normal photopic visual range to the IR, which is not dependent upon possible shape changes, etc., in the particle size distribution. For example, if the aerosol attenuation has a strong functional dependence only upon the volume content V (as suggested by Eq. (10)), a unique relationship exists (independent of V) between the extinction coefficients for two different spectral bands:

$$\beta_{aer} (IR) = G(\beta_{aer}(vis)) \quad , \qquad (11)$$

where again the link to the weather data base is provided by Eq. (9).

We are using the IR and visible portions of the spectrum only as representative examples. The above statements clearly hold for other wavelength regions as well. Equation (7) as well as the LOWTRAN example of Eq. (8) are just special cases of the more general formulation given by Eq. (11). The applicability of Eq. (11) ultimately depends upon the validity of Eq. (10). In the following paragraphs we hope to provide such a verification using the published results of Deirmendjian (Ref. 4) as well as an extensive set of Mie calculations for measured particle distributions from the Grafenwöhr field experiments.

The Deirmendjian calculations (Ref. 4) of the aerosol extinction coefficients for six different water droplet distributions, including three haze models and three cloud models, are shown in Fig. 2 for 0.7 μm and 10 μm radiation. As one proceeds from the various haze models to the cloud models the particle distributions become broader and contain a greater number of large particles as indicated by the volume of liquid water. As suggested by the earlier arguments, there is indeed a strong, smooth relationship between the extinction coefficient at each wavelength and the particulate volume. The data for other wavelengths also

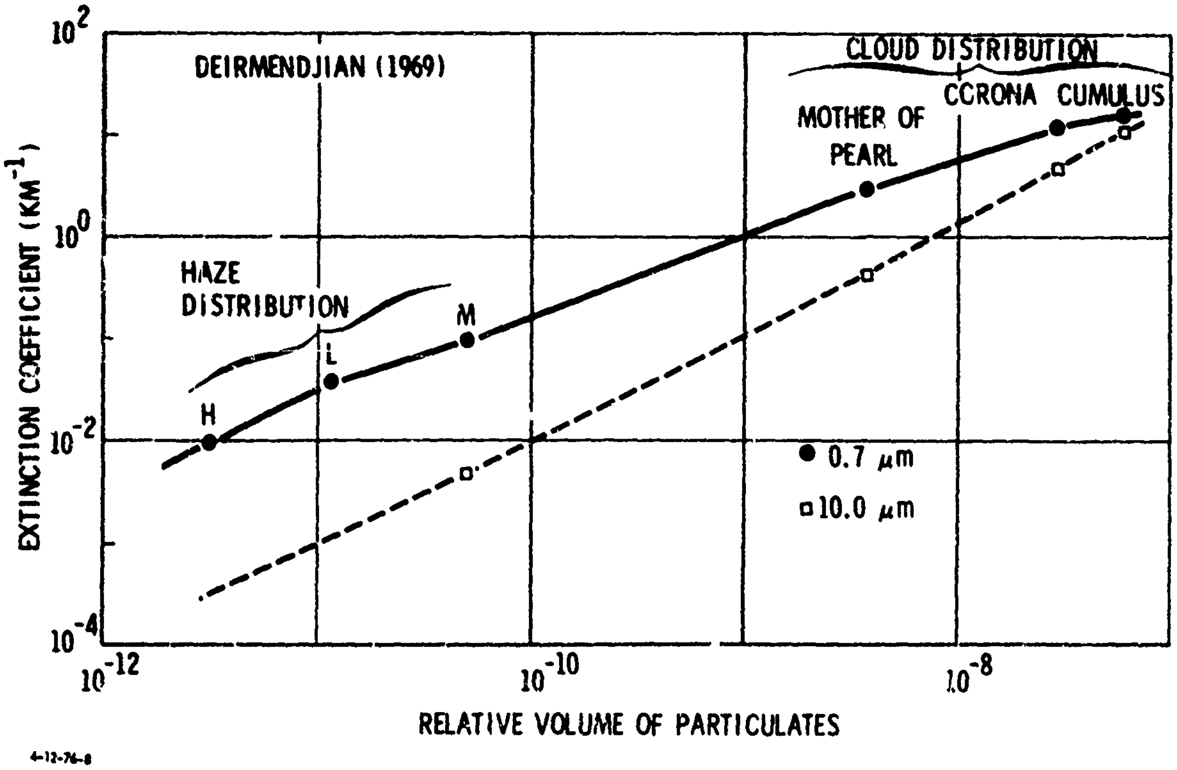

FIGURE 2. Calculated Extinction Coefficients vs. Water Content for 0.7 μm and 10.0 μm Radiation and 6 Different Aerosol Models. Mie calculations according to Deirmendjian (Ref. 4) with particle distribution functions and wavelength-dependent index of refraction given therein for liquid water droplets.

show this behavior. Furthermore, a regression analysis on β_{aer} (10 μm) versus β_{aer} (0.7 μm) yields

$$\beta_{aer}\ (10\ \mu m) \sim \beta_{aer}^{1.47}\ (0.7\ \mu m)$$

with a coefficient of determination $r^2 = 0.99$. This supports the limiting form of Eq. (7), which suggests

$$\beta_{aer}\ (10\ \mu m) \sim \beta_{aer}^{1.50}\ (0.7\ \mu m) \quad .$$

Several hundred particle distribution measurements, including balloon experiments to study the vertical lapse rate, were made using the Knollenberg Particle Measuring System (PMS) counter during the Grafenwöhr tests. Using these measured distributions (several representative ones are shown in Fig. 1), R. Pinnick* of the Army Electronics Command (ECOM) Atmospheric Sciences Laboratory performed an extensive set of Mie scattering calculations. Although the distributions inherently contain a certain degree of experimental error, the calculations employing them nonetheless provide a valid data base upon which to test our central thesis represented by Eq. (10). Figures 3-5 show the results of those calculations plotted versus liquid water content for each distribution at wavelengths of 1, 4, and 10 μm, respectively. The water content is computed from the measured distributions, assuming the aerosols were predominantly water. This does not pose a real restriction since the Mie calculations were based upon these distributions using pure liquid water optical properties. The relatively small amount of spread shown in these figures is in fact primarily due to the range of particle size restrictions imposed by the PMS counter. For example, depending upon the fogs' density, different particle size ranges

*A more extensive account of this work will be published in a forthcoming paper by R. Pinnick and R. Roberts.

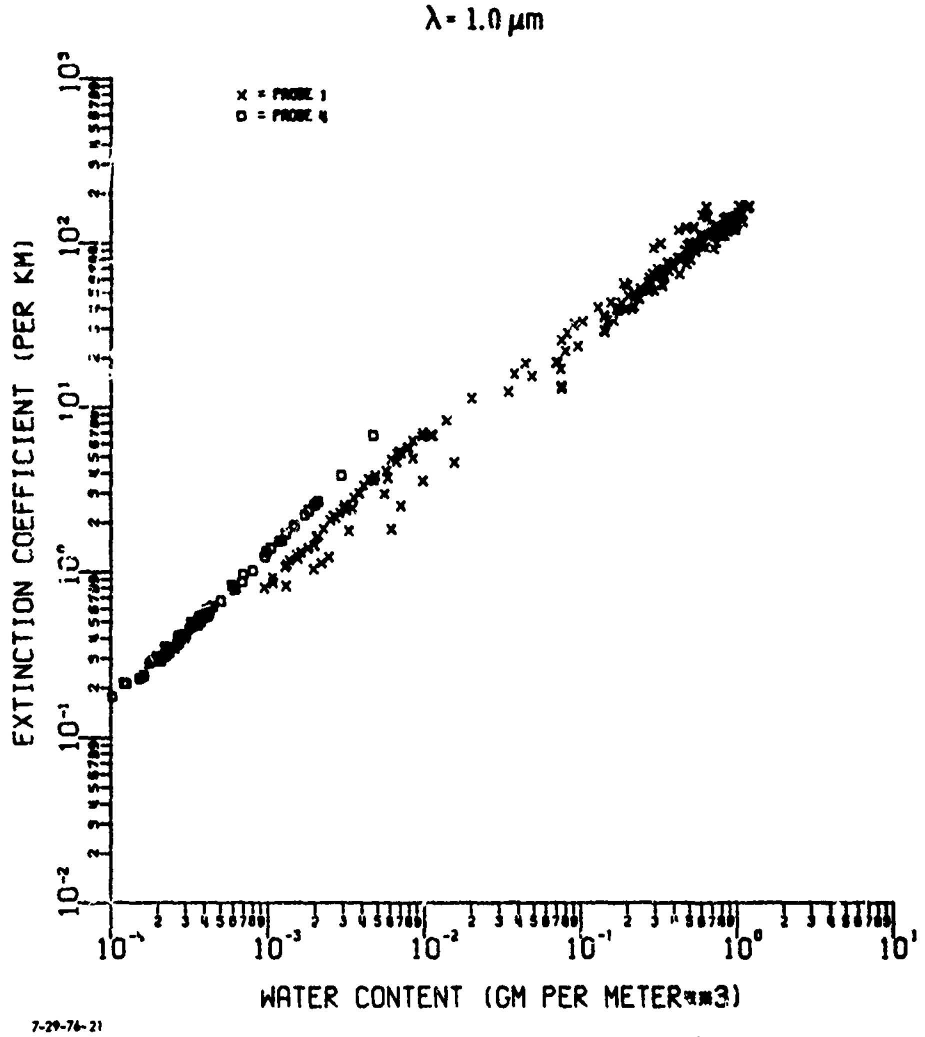

FIGURE 3. Extinction Coefficient vs. Water Content for 1 μm Radiation and Measured Particle Distributions from Grafenwöhr. Each point represents a distinctly different measured distribution. Mie calculations performed with the liquid water optical properties of Hale and Querry (Ref. 6).

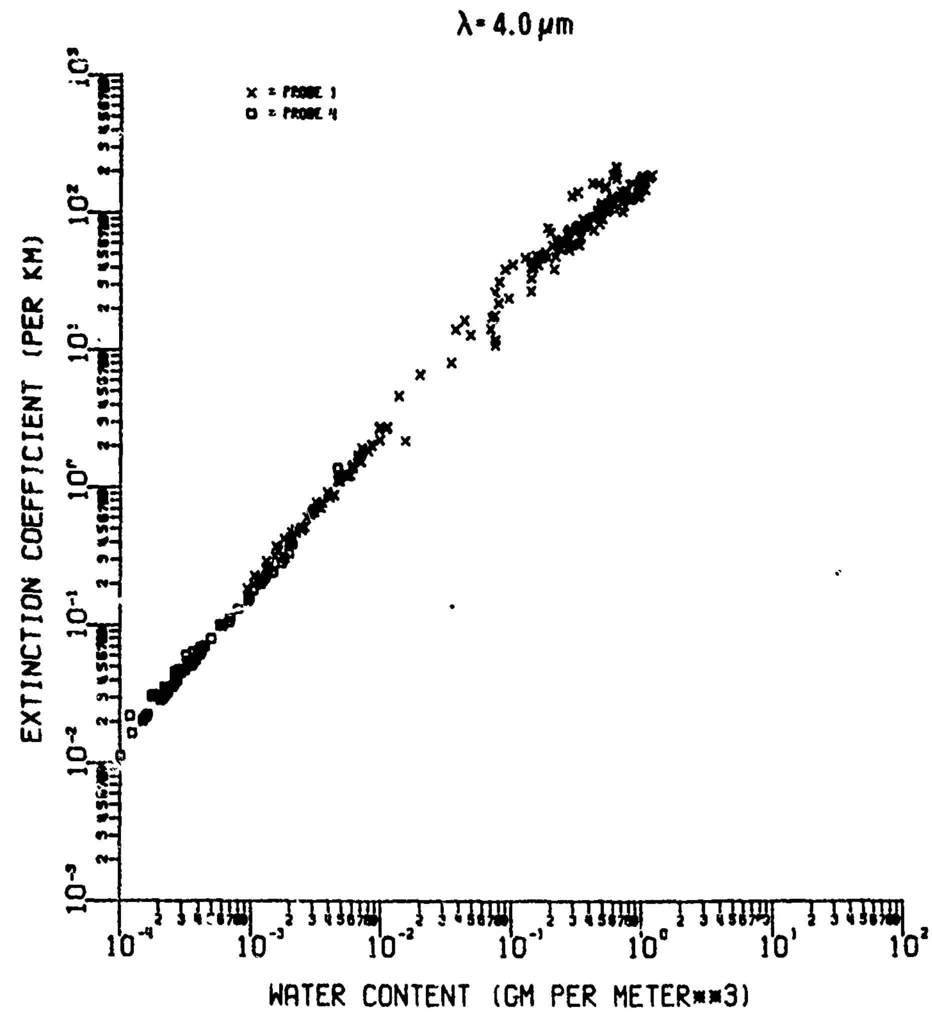

FIGURE 4. Extinction Coefficient vs. Water Content for 4 μm Radiation and Measured Particle Distributions from Grafenwöhr. Each point represents a distinctly different measured distribution. Mie calculations performed with the liquid water optical properties of Hale and Querry (Ref. 6).

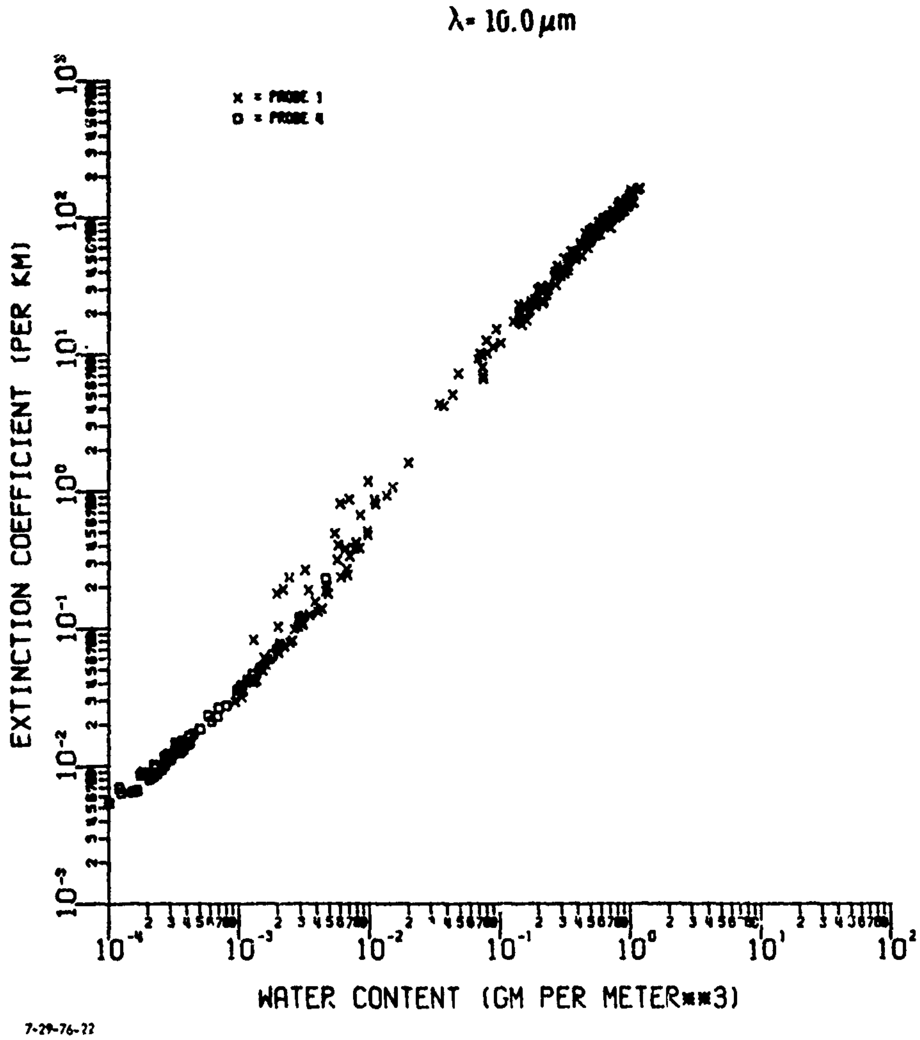

FIGURE 5. Extinction Coefficient vs. Water Content for 10 μm Radiation and Measured Particle Distributions from Grafenwöhr. Each point represents a distinctly different measured distribution. Mie calculations performed with the liquid water optical properties of Hale and Querry (Ref. 6).

were used (indicated by o and x in Figs. 3-5). A measurement made using a given particle setting on the equipment therefore necessarily excludes some particles otherwise measured using a different range setting. In general, the points clustered most tightly on a given line in Figs. 3-5 represent a single range setting for the instrument. However, even neglecting the instrumental artifacts, the match between β_{aer} and V is still quite good--again supporting the contention of Eq. (10). Finally, one finds for this 311-point data base that

$$\beta_{aer}\ (10\ \mu m) \sim \beta_{aer}^{1.49}\ (1\ \mu m)$$

and

$$\beta_{aer}\ (4\ \mu m) \sim \beta_{aer}^{1.42}\ (1\ \mu m) \quad ,$$

again supporting Eq. (7). It should be noted that each of the above sets of calculations were performed for liquid water complex indices of refraction. In both cases the real and imaginary indices are strong functions of the wavelength. The appropriate references for the Deirmendjian computations are cited in his text (Ref. 4), whereas the Pinnick calculations are representative of the Hale and Querry (Ref. 6) measurements for liquid water.

The main point we wish to emphasize here is that the above results are indicative of a large number of distributions. For the case of the Grafenwöhr PMS measurements the particle size distributions vary drastically in shape from case to case (much more than is indicated in Fig. 1). Although the PMS counter excluded particles having radii greater than 8 μm, we have found that this artifact of the distribution measurement does not affect the results shown in Figs. 3-5 to any significant degree. This is most likely due to the rapid exponential falloff of n(r) versus r, as illustrated in Fig. 1. Furthermore, the Deirmendjian calculations have no such restrictions and still show a smooth functional relationship between aerosol extinction and liquid water content. This is also the case for the broad large-particle distributions representing the three cloud models (cf. Fig. 2).

As further support for the contention that aerosol extinction is most strongly dependent upon liquid content rather than the explicit functional form of the distribution, Katz (Ref. 7) has performed an analysis analogous to the one in this paper for the maritime aerosol environment. Using a maritime aerosol distribution (Ref. 8) whose form depends upon meteorological factors such as wind velocity and relative humidity, Katz was able to show an even closer relationship than is indicated in Figs. 3-5 for extinction versus liquid content and for wavelengths from the visible to long-wavelength IR region of the spectrum. In fact, this relationship was found even though his particle index of refraction was dependent upon the meterological parameters through a mix ratio varying between pure liquid water and sea salt.

The conclusion of the above discussion is that for a large number of different measured and assumed distributions the volume of particulate is in fact the most critical parameter in determining the aerosol extinction, and thus scaling laws and subsequent analysis based upon Eqs. (10) and (11) should be valid. Work by Hänel (Ref. 9) and his collaborators together with our own current efforts* indicates that a similar dependence exists for solid particulates as well.

*Work in progress by R. Pinnick and R. Roberts.

III. CONCLUSIONS

Most current aerosol models suffer considerably (especially for fog conditions) from reliance upon a single or finite number of scaled particle size distributions. It is clear from the Grafenwöhr measurements and the analysis presented here that this methodology is not valid. The outcome of using any prescribed particle distribution is a linearized model as given in Eq. (8). A major part of the motivation for this work was to demonstrate that such a restrictive assumption is unnecessary and contradictory to modeling the real atmospheric aerosol environment, particularly for limited visibility conditions. Our extinction versus volume content analysis shows that for a wide variety of cases (such as the Grafenwöhr measurements) the volume content of particulate along the transmission path is the most important parameter in determining the aerosol extinction. Thus, a more general and valid aerosol scaling model can be derived (as given in Eq. (11)) that is independent of the intricate behavior of the particle distribution. Implicit support for this contention is also provided by the Grafenwöhr transmission measurements shown in the Appendix. This paper also suggests that a relatively simple measurement of the liquid content along a given transmission path could provide a direct indication of the IR propagation along that path. One very enticing possibility for a real-time and remote measurement would be to use a visible LIDAR technique. The measured backscatter profile represents a sensitive measure of the liquid water content along the prescribed LIDAR path (Ref. 10). Thus, one is presented with the exciting possibility of rapidly and remotely monitoring the IR atmospheric propagation characteristics using a laser ranging device operating in the visible part of the spectrum. An experimental test of this hypothesis will be carried out as part of the Army Night Vision Laboratory atmospheric propagation program in February 1977.

REFERENCES

1. Air Force Cambridge Research Laboratories, Atmospheric Transmittance from 0.2 to 28.5 μm: Computer Code LOWTRAN 3, AFCRL-TR-75-0253, J. E. A. Selby and R. A. McClatchey, May 1975.

2. Institute for Defense Analyses, Infrared Continuum Absorption by Atmospheric Water Vapor in the 8-12 μm Window, IDA Paper P-1184, R. E. Roberts, L. M. Biberman, and J. E. A. Selby, April 1976.

3. H. C. Van de Hulst, Light Scattering by Small Particles, John C. Wiley and Sons, New York, 1957.

4. D. Deirmendjian, Electromagnetic Scattering on Spherical Dispersions, American Elsevier Publishing Co., New York, 1969.

5. W. E. K. Middleton, Vision Through the Atmosphere, University of Toronto Press, 1968.

6. G. M. Hale and M. R. Querry, "Optical Constants of Water in the 200-nm to 200-μm Wavelength Region," Appl. Opt., Vol. 12, No. 555, 1973.

7. B. Katz, White Oak Laboratory, Naval Surface Weapons Center, personal communication, 1976.

8. Lockheed Palo Alto Research Laboratory, Aerosol Distributions in Maritime Air, W. C. Wells, G. Gal, and M. W. Munn, 1976.

9. G. Hänel, "The Properties of Atmospheric Aerosol Particles as Functions of the Relative Humidity at Thermodynamic Equilibrium with the Surround Moist Air," Adv. Geophysics, Vol. 19, 1976.

10. E. E. Uthe and R. J. Allen, "A Digital Real-Time LIDAR Data Recording, Processing, and Display System," J. Optical and Quantum Electronics, Vol. 7, No. 121, 1975.

APPENDIX

SCOPE OF EXPERIMENTAL DATA BASE

In order to characterize the atmospheric transmission for a quantified German winter environment the Army Night Vision Laboratory conducted a series of field measurements at Grafenwöhr, FRG, from November 1975 to January 1976.

Since the Grafenwöhr field tests were performed during the winter, for most conditions the most significant contribution to the atmospheric attenuation was from fine-particle aerosols such as haze and fog as well as large particles such as rain and snow. In the main text we presented arguments which suggested a strong relationship between aerosol extinction coefficients in different spectral bands. Clearly the same relationship then exists for transmission as well. Towards the end of December 30 and during December 31, 1975 a particularly clean set of measurements was made on what appears to be a textbook example of stable ground fog conditions. In Fig. A-1 we have plotted the transmissions for the 0.8-1.1 μm and 3.4-4.1 μm bands as functions of the 8.1-12.0 μm transmission.* The figure shows that there is perhaps a slight favoring of the 8.1-12.0 μm region over the competitive 3.4-4.1 μm IR band. The transmission in the IR regions is significantly greater than in the 0.8-1.1 μm band. The particle distribution and composition measurements for this time period bear this out well. Detailed comparison of Grafenwöhr transmission measurements and the aerosol theory outlined here is beyond the scope of this paper. It will, however, be the subject of a forthcoming IDA paper.

*The molecular absorption component has not been normalized out of these curves. It is, however, constant to within a few percent for the conditions cited in Fig. A-1.

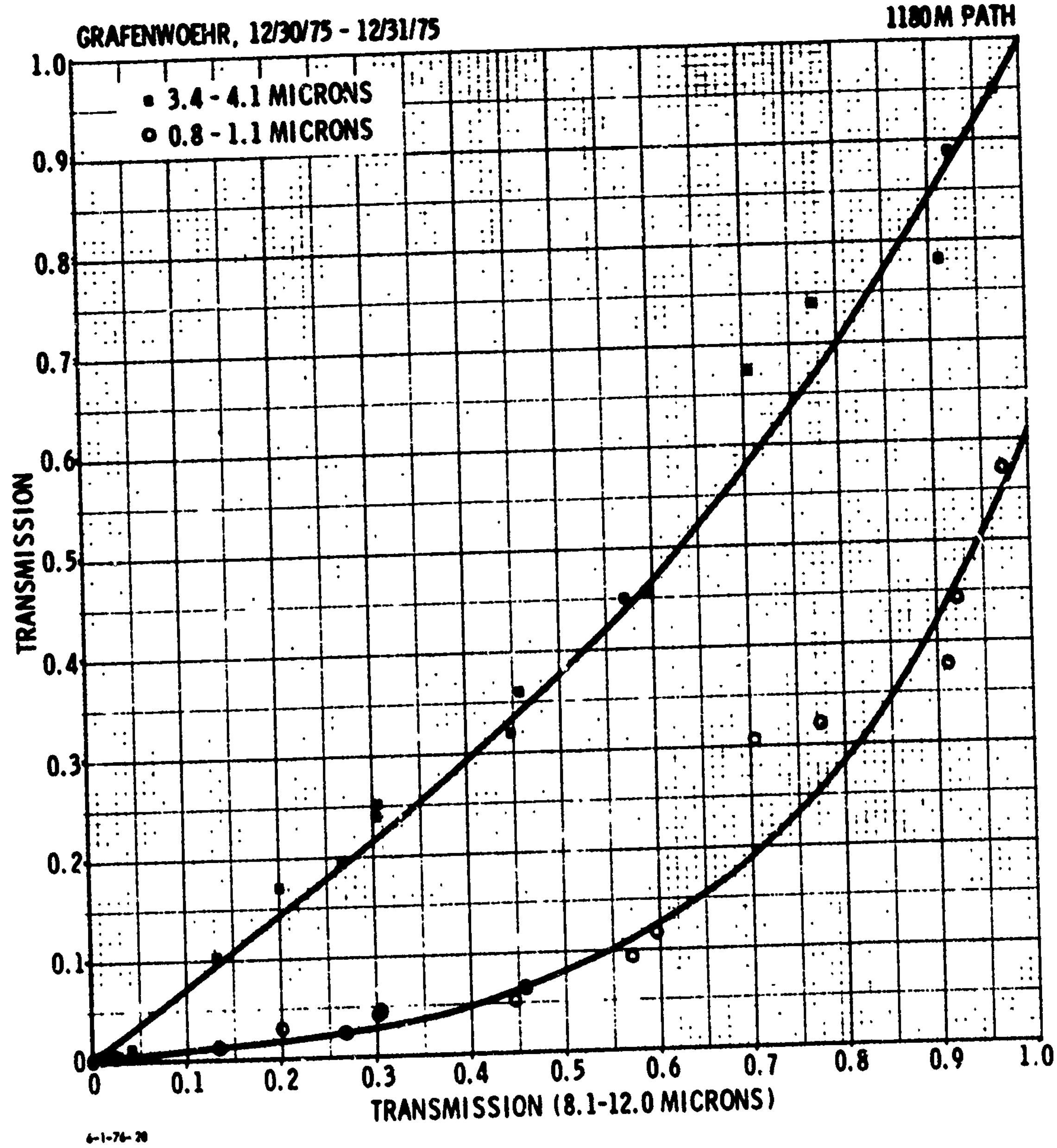

FIGURE A-1. Transmission in the 3.4-4.1 μm and 0.8-1.1 μm Bands versus the 8.1-12.0 μm Band, Grafenwöhr.

The measured particle distributions together with the measured transmission and Air Force visibility estimates for representative points during 30-31 December are shown in Fig. 1 in the main text. The trend is quite clear. The left curve represents the best of the visibility and transmission, which are growing progressively poorer with time and with the successive shifting of the curves to the right. There is a drastic change in the shape of the distributions, the larger particles having a greater representation as the visibility drops. This again underlines the necessity of having aerosol models that are not explicitly dependent upon a single representative size distribution as is the case for LOWTRAN. LOWTRAN 3b will include additional aerosol models, although none of these will be representative of fog conditions such as those occurring at Grafenwöhr. The more general aerosol scaling models discussed in the earlier portion of this paper can accommodate this flexibility.

In this appendix we have made no attempt to present a comprehensive review of the Grafenwöhr trials. That will form the subject matter of a more comprehensive report sponsored jointly with the Army Night Vision Laboratory (NVL) and Atmospheric Sciences Laboratory (ASL). Instead, we have tried to highlight some of the most important elements of the field measurements as they relate to atmospheric modeling and sensor performance in particular.

A study is currently in progress at IDA which shows that similar relationships exist between transmission bands in other different environments such as English maritime and Camp A. P. Hill, Virginia. That study lends further experimental documentation to the proposed aerosol model. We are also carrying out a more detailed comparison of aerosol models (derived from computations like those presented in this paper) with a more extensive limited-visibility data base from Grafenwöhr.*

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*R. Bergemann (NVL), R. Pinnick (ASL), R. Roberts (IDA), and M. Sola (NVL), work in progress.